Rocketdyne Division
Rockwell International

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SPACE SHUTTLE
ORBIT MANEUVERING ENGINE
REUSABLE THRUST CHAMBER

(NAS9-12802)

Prepared for

National Aeronautics and Space Administration
Johnson Spacecraft Center
Houston, Texas

# TASK X DATA DUMP
# COMPARISON OF 8- AND 10-INCH DIAMETER THRUST CHAMBERS

Prepared by

R. P. Pauckert
SS/OME Principal Engineer
Advanced Projects

R. D. Tobin
Advanced Projects

APPROVED BY

R. D. Paster
SS/OME Project Engineer
Advanced Projects

R. D. Paster
Acting SS/OME Program Manager
Advanced Programs



(NASA-CR-141675) SPACE SHUTTLE ORBIT MANEUVERING ENGINE REUSABLE THRUST CHAMBER. TASK 10: DATA DUMP COMPARISON OF 8- AND 10-INCH DIAMETER THRUST CHAMBERS (Rocketdyne) 28 p HC $3.75 CSCL 21H G3/20
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ROCKETDYNE DIVISION OF ROCKWELL INTERNATIONAL CORPORATION
6633 Canoga Avenue, Canoga Park, CA 91304

# INTRODUCTION

The point design SSOME Regeneratively Cooled Orbit Maneuvering Engine described by Rocketdyne in the Task I, II Data Dump includes a regeneratively cooled thrust chamber having a contraction ratio of 2 and an injector-to-throat distance of 14.7 inches. The chamber has a diameter of 8.2 inches at the injector end and was designed with constant width channels from the injector through the throat region into the diverging section where a step change in the channel width was made to reduce the weight of the chamber. Since that Data Dump was prepared, potential advantages in performance, stability, and heat transfer characteristics have been indicated for a chamber having a contraction ratio 3 instead of 2. Also, significant weight advantages have been shown for fabrication of a chamber using constant land thicknesses instead of constant channel widths. Finally, experimental heat flux profiles became available for both chambers. The purpose of this analytical and design study was to compare the high and low contraction ratio thrust chambers and the two channel design concepts on the basis of weight, pressure drop, and performance. Only the basic thrust chamber assembly was considered in this analysis. The assembly consists of the injector, the regeneratively cooled thrust chamber, and the radiation cooled nozzle. Engine design factors from the Rocketdyne Data Dump, ASR 72-238, and vehicle trade factors furnished by NASA were used in the study.

# SUMMARY

Three chamber configurations were analyzed: 1) an 8-inch diameter ($\epsilon_c$ = 2) chamber having constant width channels; 2) an 8-inch diameter chamber having constant width lands; and 3) a 10-inch diameter chamber ($\epsilon_c$ = 3) having constant width lands. Component weights, pressure drops, and nozzle performance were calculated for each configuration using experimental heat transfer data. OMS trade factors were used to convert the weights and pressure drops to equivalent specific impulse values for: 1) constant OMS inert weight, and 2) constant OMS wet (tanked) weight.

The resulting weights, pressure drops, and performance values summarized below indicate the superiority of the constant width land over the constant width channel configuration. The 8-inch diameter chamber provides a significant equivalent performance gain relative to the 10-inch chamber based on constant OMS inert weight but a slight performance loss based on wet weight.

| Configuration | $\epsilon_c$ | $\Delta$Weight, Lb | $\Delta$Inlet Press., PSIA | $\Delta$Nozzle $I_s$, Sec | $\Delta$Equiv. $I_s$, Sec Inert | Wet |
|---|---|---|---|---|---|---|
| Constant Channel | 2 | Nominal | Nominal | Nominal | Nominal | |
| Constant Land | 2 | -6.5 | -3.6 | 0 | 7.0 | 0.3 |
| Constant Land | 3 | 6.6 | -3.8 | 0.9 | 3.8 | 1.0 |

# DISCUSSION

The initial Rocketdyne regeneratively cooled OME design was perturbed to determine the effects of changing the design contraction ratio and the fabrication technique with respect to channel cutting. Three chamber configurations were investigated: 1) contraction ratio of 2 and constant channel width; 2) contraction ratio of 2 and constant land width; 3) contraction ratio of 3 and constant land width.

## BASIC ENGINE DESIGN AND GROUND RULES

The Rocketdyne regeneratively cooled OME design is shown in Fig. 1. The engine includes the regeneratively cooled chamber, radiation nozzle, injector,propellant valves, gimbal ring and gimbal bearing attachments, propellant ducting, electrical harness, and pneumatic package. A weight breakdown of these components is shown in Table 1. Only the first three items are included in the weight analysis. Changes in the contraction ratio and chamber length of the magnitude being considered would have little if any effects on the weights of the other components.

Ground rules for the study are summarized in Table 2. The heat flux profiles are based and experimental data taken with Rocketdyne ($\epsilon_c = 2$) and Bell Aerosystems ($\epsilon_c = 3$) chambers. Two-dimensional analyses were used to calculate the temperature distribution for the chamber with constant-width channels. The simpler, one-dimensional analyses were used for the chambers having constant-width lands. The narrow (0.040 inch) width chosen for the land results in lower wall temperature because the heat flux is uniformly distributed. To verify this, one- and two-dimensional analyses were made of chamber with $\epsilon_c = 2$. The one-dimensional analysis indicated a wall temperature of 389.5 F in contact with the coolant. The results of the two-dimensional analysis, shown in the schematic computer printout of Fig. 2 , indicate essentially the same temperatures.

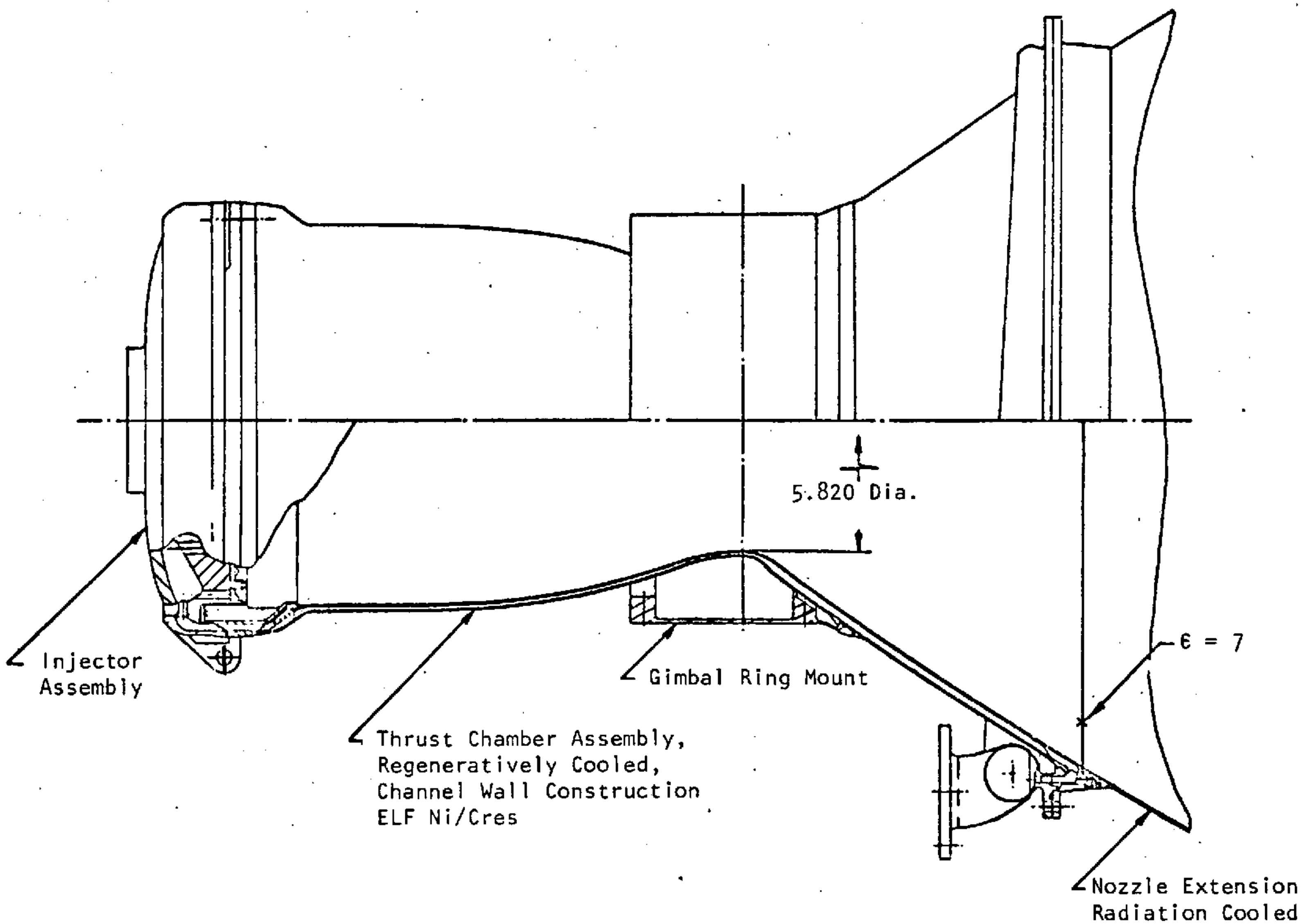


Figure 1. OME Thrust Chamber Assembly Flight Configuration

TABLE I

ORBIT MANEUVERING ENGINE
WEIGHT BREAKDOWN

| | WEIGHT, POUNDS |
|---|---|
| REGENERATIVE CHAMBER | 37.4 |
| RADIATION NOZZLE | 41.2 |
| INJECTOR | 23.6 |
| PROPELLANT VALVE | 38.0 |
| GIMBAL RING BEARING ATTACHMENTS | 26.0 |
| GIMBAL ACTUATORS | - |
| DUCTING | 10.7 |
| ELECTRIC | 2.7 |
| PNEUMATIC PACKAGE | 15.9 |
| TOTAL | 195.5 |

TABLE 2

GROUND RULES

COMPONENTS: INJECTOR, CHAMBER, NOZZLE

REGENERATIVELY COOLED NOZZLE AREA RATIO: 7

NOZZLE AREA RATIO: 72

CHAMBER LENGTH FOR $\epsilon_c$ = 2: 14.7 INCHES
NOZZLE % LENGTH FOR $\epsilon_c$ = 2: 70
CHAMBER LENGTH FOR $\epsilon_c$ = 3: 12 INCHES
NOZZLE % LENGTH FOR $\epsilon_c$ = 3: 73

INJECTOR $\Delta P$ NOT DEPENDENT ON $\epsilon_c$

EXPERIMENTAL HEAT FLUX PROFILES

HOT AND COLD WALL THICKNESSES: 0.030 INCHES

REGEN SAFETY FACTOR: 1.5 AT OFF DESIGN

8 IN. DIA. CONST. L=.040IN.   ANALYZE AT NOM. CONDITIONS

STATION NO. = 31     TWG(1-D) = 599.89 F
X (INCHES) = -8.0000     TWC(1-D) = 389.45 F
AREA RATIO = 2.0000     HC(1-D) = 0.8018E-02

| CHANNEL DIMENSIONS (IN.) | THERMAL CONDUCTIVITY (BTU/IN-SEC-F) | COMBUSTION-GAS PARAMETERS | COOLANT PARAMETERS |
|---|---|---|---|
| | | | TBULK = 183.81 F |
| WALL THICKNESS = 0.0300 | | | |
| CHANNEL HEIGHT = 0.0911 | WALL = 0.2350E-03 | TAW = 3049.69 F | TB/TWC EXPONENT = 0.0 |
| CHANNEL WIDTH = 0.1771 | CLOSEOUT = 0.1000E-02 | HG = 0.6730E-03 | MAX. CURVATURE = 1.000 |
| LAND WIDTH = 0.0400 | | (BTU/IN2-S-F) | HC(REF.) = 0.8018E-02 |
| CLOSEOUT THICK.= 0.0300 | | | (BTU/IN2-S-F) |

BETA = 1.963     AT ITERATION NUMBER 25

CONVERGENCE SATISFIED AT ITERATION = 148

HEAT BALANCE = 0.6434E-03     MAXIMUM DT/T = 0.7801E-04 AT NODE 21

TEMPERATURES (F)

| | | | | | | |
|---|---|---|---|---|---|---|
| 582.98 | 582.82 | 582.43 | 582.23 | 590.46 | 595.27 | 596.65 |
| 512.82 | 512.47 | 511.54 | 510.71 | 520.23 | 525.20 | 526.57 |
| 444.40 | 443.35 | 440.41 | 436.70 | 450.52 | 455.52 | 456.77 |
| 380.79 | 378.39 | 370.83 | 357.00 | 381.80 | 386.26 | 387.25 |
| 253.75 | 251.81 | 245.97 | 225.15 | | | |
| 207.08 | 206.38 | 204.32 | 200.97 | | | |
| 189.70 | 189.55 | 189.08 | 188.25 | 186.63 | 185.94 | 185.74 |
| 188.94 | 188.85 | 188.59 | 188.21 | 186.80 | 186.09 | 185.87 |
| 188.58 | 188.52 | 188.36 | 188.13 | 186.88 | 186.17 | 185.94 |
| 188.46 | 188.42 | 188.30 | 188.10 | 186.91 | 186.20 | 185.96 |

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FINAL COOLANT FILM COEFFICIENTS

| | | | |
|---|---|---|---|
| 0.008018 | 0.008018 | 0.008018 | 0.008018 |
| 0.008018 | | | |
| 0.008018 | | | |
| 0.008018 | 0.008018 | 0.008018 | 0.008018 |

FIN FACTOR = 1.0232

Figure 2. Two-Dimensional Thermal Analysis of Channel Section - Constant Land Width Design

If a land width much greater than 0.040 inches must be used (generally because of fabrication constraints ), the two-dimensional penalty can be significant. For example, the two-dimensional analysis of a configuration with a 0.103-inch wide land (Fig. 3) resulted in a maximum coolant side wall temperature of 402 F compared to the one-dimensional value of 389 F. The increased corner temperature implies a higher local heat flux and resultant reduced local safety factor.

All chambers were designed to have a safety factor of 1.5 at the following off-design conditions: 100 F fuel inlet temperature, 120 psia chamber pressure and 1.73 propellant mixture ratio.

Guided by previous designs and the data shown in Figs.4 and 5, 120 channels were selected for all chambers. Land widths of 0.04 inches at the throat and inner and outer wall thicknesses of 0.03 inches were used for consistency on both chambers. The low contraction ratio chamber could use a 0.05-inch constant land if required by fabrication constraints. Use of the 0.05-inch land on the high contraction ratio chamber would result in branching. In practice, a very slight reduction in the contraction ratio from the value of 3:1 would be required to eliminate the branching constraint. Alternatively, the extraneous lands could be machined out. This would result in a maximum channel width of 0.26 inches which would be marginal from the stress consideration and require further analysis. A more detailed discussion of branching of lands follows.

8 IN. DIA CONST W=.200/.114 ANALYZE AT NOM. CONDITIONS

STATION NO. = 31 TWG(1-D) = 599.41 F
X (INCHES) = -8.0000 TWC(1-D) = 388.89 F
AREA RATIO = 2.0000 HC(1-D) = 0.8040E-02

| CHANNEL DIMENSIONS (IN.) | THERMAL CONDUCTIVITY (BTU/IN-SEC-F) | COMBUSTION-GAS PARAMETERS | COOLANT PARAMETERS |
|---|---|---|---|
| WALL THICKNESS = 0.0300 | | | TBULK = 183.77 F |
| CHANNEL HEIGHT = 0.0850 | WALL = 0.2350E-03 | TAW = 3049.69 F | TB/TWC EXPONENT = 0.0 |
| CHANNEL WIDTH = 0.1140 | CLOSEOUT = 0.1000E-02 | HG = 0.6730E-03 | MAX. CURVATURE = 1.000 |
| LAND WIDTH = 0.1031 | | (BTU/IN2-S-F) | HC(REF.) = 0.8040E-02 |
| CLOSEOUT THICK.= 0.0300 | | | (BTU/IN2-S-F) |

BETA = 1.862 AT ITERATION NUMBER 25

CONVERGENCE SATISFIED AT ITERATION = 68
HEAT BALANCE = 0.29295-03 MAXIMUM DT/T = 0.8801E-04 AT NODE 1

TEMPERATURES (F)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | 677.31 | 670.92 | 653.37 | 631.21 | 617.74 | 611.52 | 609.72 |
| | 611.53 | 604.59 | 585.52 | 560.34 | 547.09 | 541.09 | 539.33 |
| | 550.41 | 542.68 | 519.74 | 485.24 | 474.47 | 469.47 | 467.97 |
| | 494.58 | 485.85 | 457.89 | 402.17 | 400.23 | 396.88 | 395.76 |
| | 368.66 | 360.18 | 333.73 | 286.23 | | | |
| | 288.56 | 283.40 | 266.92 | 239.30 | | | |
| | 238.79 | 236.56 | 230.36 | 219.55 | 212.35 | 208.83 | 207.72 |
| | 235.83 | 233.95 | 228.60 | 220.67 | 214.13 | 210.50 | 209.34 |
| | 234.13 | 232.43 | 227.70 | 221.15 | 215.11 | 211.51 | 210.33 |
| | 233.57 | 231.94 | 227.42 | 221.28 | 215.42 | 211.94 | 210.66 |

FINAL COOLANT FILM COEFFICIENTS

0.008040 0.008040 0.008040 0.008040
0.008040
0.008040
0.008040 0.008040 0.008040 0.008040

FIN FACTOR = 0.9579

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Figure 3. Two-Dimensional Thermal Analysis of Channel Section - Constant Land Width Design

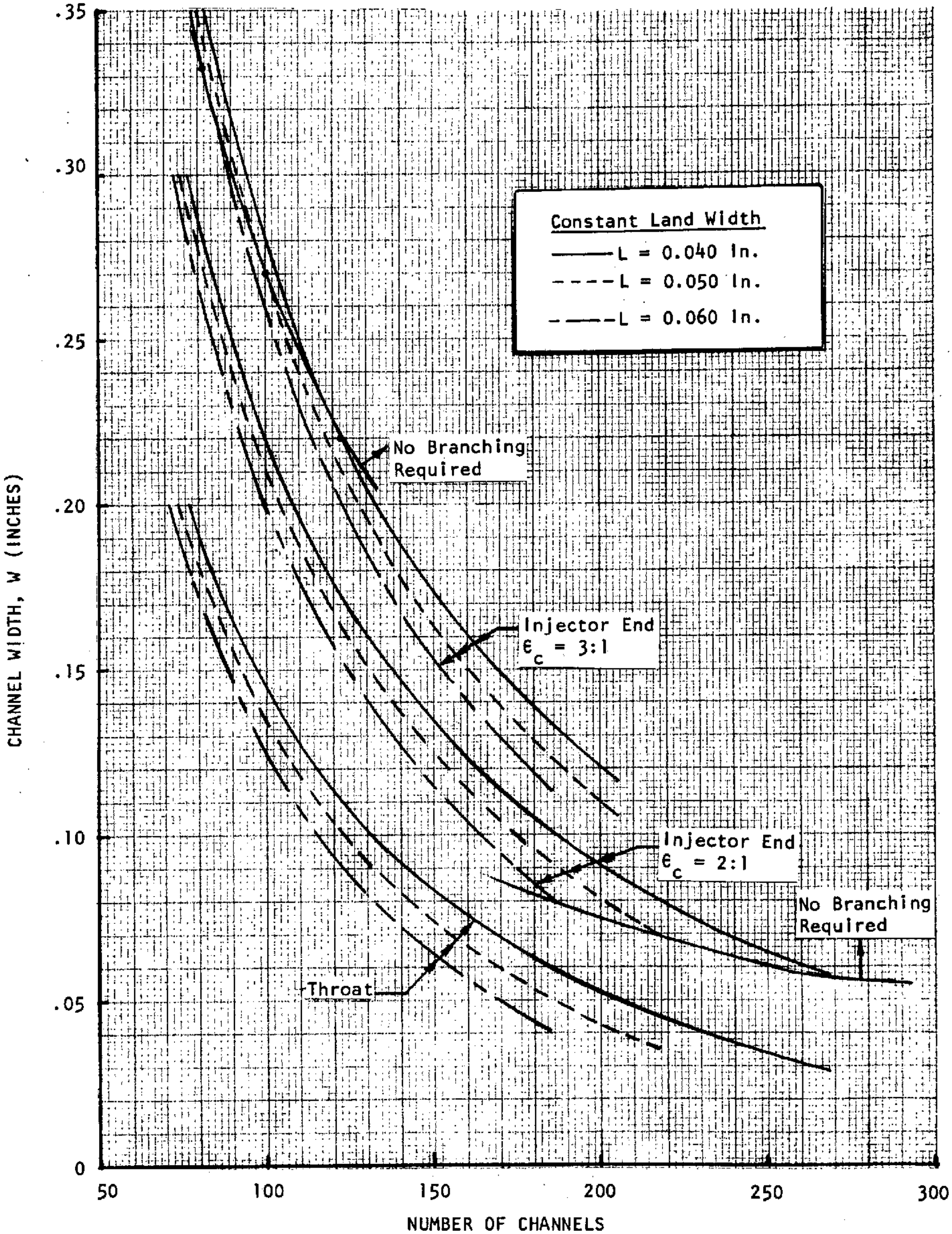


Figure 4. Channel Geometry Relationships For Constant Land Width Chamber Design

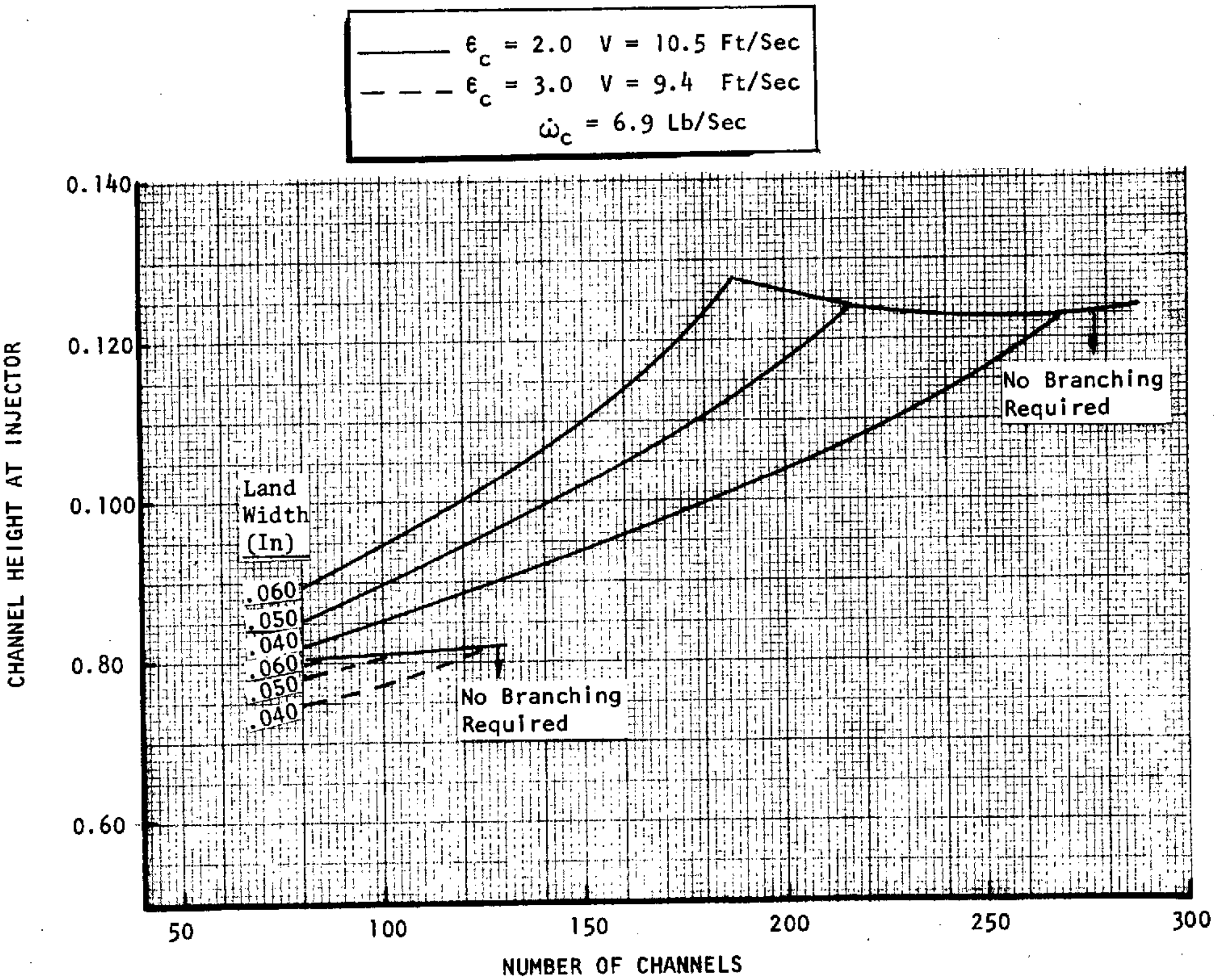


Figure 5. Channel Height Requirements For Constant Land Width Chamber Designs

CHANNEL GEOMETRY

Figures 4 and 5 are useful in making the initial estimates of design parameters for chambers having constant width lands. The geometric relationships between channel width, land width, and number of channels are shown in Fig. 4. If the number of channels is small or the land width is large, as the straddle mill cutter moves from the throat region towards the injector-end the increasing chamber circumference results in the initiation and formation of a gradually widening land extraneous to the desired constant-width land. This extraneous land would probably have to be at least partially machined away to avoid the feather-edge pointing toward the throat region and may, in the extreme, present an unacceptably thick land near the injector-end. The curves shown in Fig. 4 indicate the combinations of channel and land widths and number of channels which can be used to avoid branching and extraneous lands. The branching constraint does not unduly restrict the combination of design parameters available for a constant land chamber with a contraction ratio of 2:1 using a straddle mill cutter. For the chamber with a contraction area ratio of 3:1 and a land width restricted to 0.040 inches or larger for fabrication and structural reasons, the number of channels must be restricted to 120 or less to avoid channel branching. This results in a channel width of approximately 0.225 inches near the injector-end. Reducing the number of channels below 120 results in wider channels which are not structurally acceptable. The sensitivity of the branching constraint to the chamber contraction ratio is obvious in Fig. 4 where it is shown that for a land width of 0.040 inches the maximum allowable number of channels is approximately doubled in the 2:1 contraction ratio chamber compared to that of the 3:1 chamber. The constraint on minimum channel width is reduced by almost a factor of 4 for the lower contraction area chamber.

The constant land design is not unduly constrained by channel height limits as shown in Fig. 5. For typical land widths and number of channels, the minimum channel height is greater than 0.08 inches for the small diameter chamber and greater than .075 inches for the larger diameter chamber. Selecting a large number of channels could result in a large ratio of the land (channel) height to width ratio which would be somewhat difficult to machine. However, this only occurs when the number of channels exceeds about 200 for the smaller diameter chamber.

## ANALYSES AND RESULTS

The three chambers described above were designed and analyzed to determine pressure drops and channel height profiles. Weights were calculated for the chambers, injectors, and radiation nozzles. The chamber with the higher contraction area ratio is 2½ inches shorter than the other chambers so that a longer, higher performing nozzle can be used. Space Shuttle trade factors were used to convert differences in weight and pressure drop between the chambers to effective specific impulse differences. Combining these with the nozzle performance difference resulted in comparisons in performance between the three chambers for injectors with performance assumed to be equal. Alternatively, the injector performance requirements for equal effective specific impulse were determined.

### Thermal Analyses

The land width and height profiles required to maintain the required safety factor at off design conditions in the chamber having constant channel widths are shown in Figs. 6 and 7. The channel width and height profiles for the chambers having constant land widths are shown in Figs. 8 thru 11. Pressure profiles for the three chambers are shown in Figs. 12 thru 14. The jacket pressure drops and life expectancies are summarized below.

| Construction | $\epsilon_c$ | Jacket $\Delta P$, psi | life, cycles |
|---|---|---|---|
| Constant Channel | 2 | 7.7 | 5100 |
| Constant Land | 2 | 4.1 | 5100 |
| Constant Land | 3 | 3.9 | 4500 |

The drop for the chamber with low contraction ratio and constant width channels is less than that measured on Rocketdyne's Demonstrator and Integrated thrust chambers because the latter were designed to accommodate a theoretical heat flux which was considerably higher than the experimental profile near the injector. Experimental heat flux profiles are shown in Figs. 15 and 16.

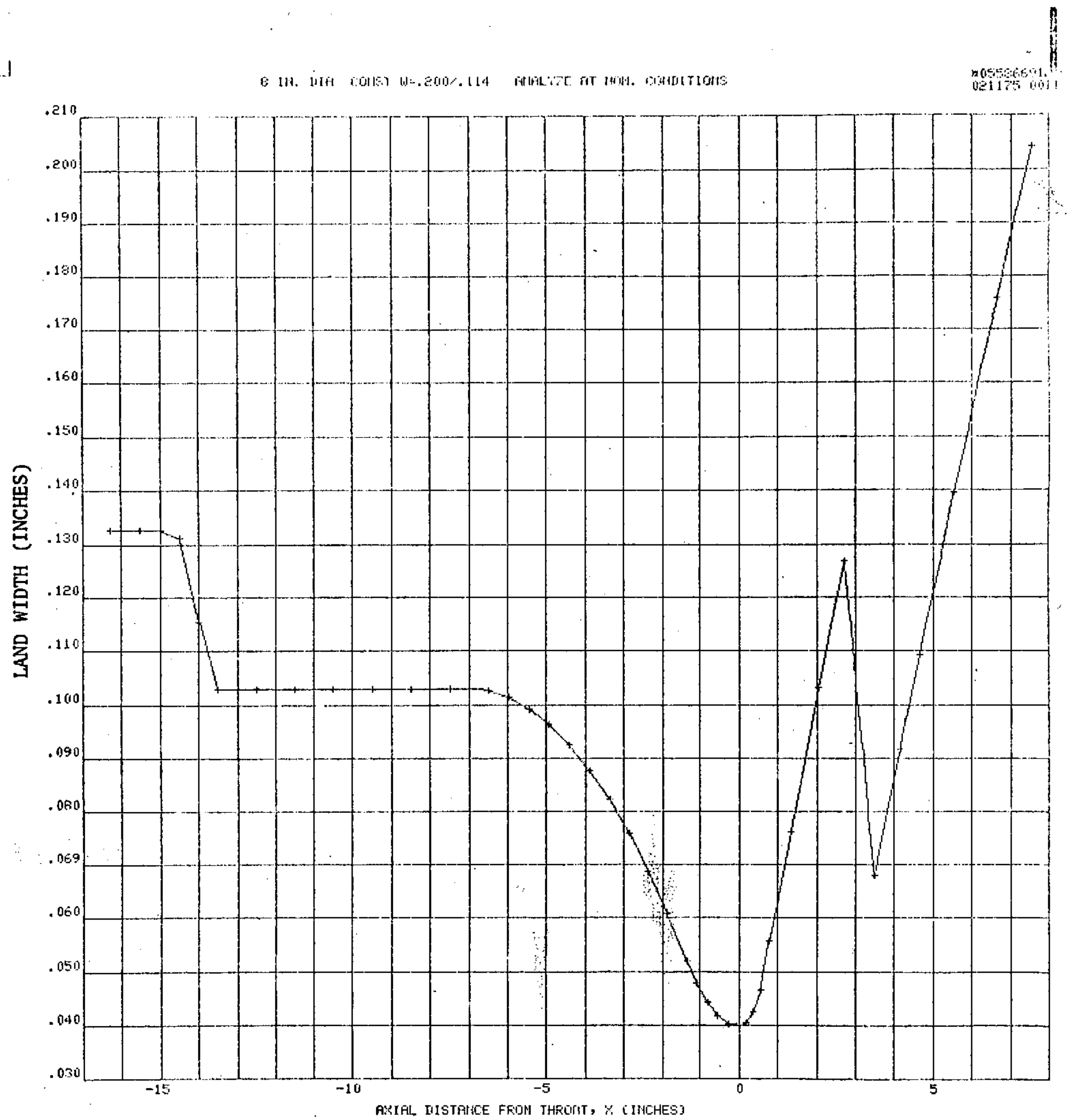


**Figure 6. Land Width Profile For 8-Inch Diameter Chamber - Constant Channel Width Design**

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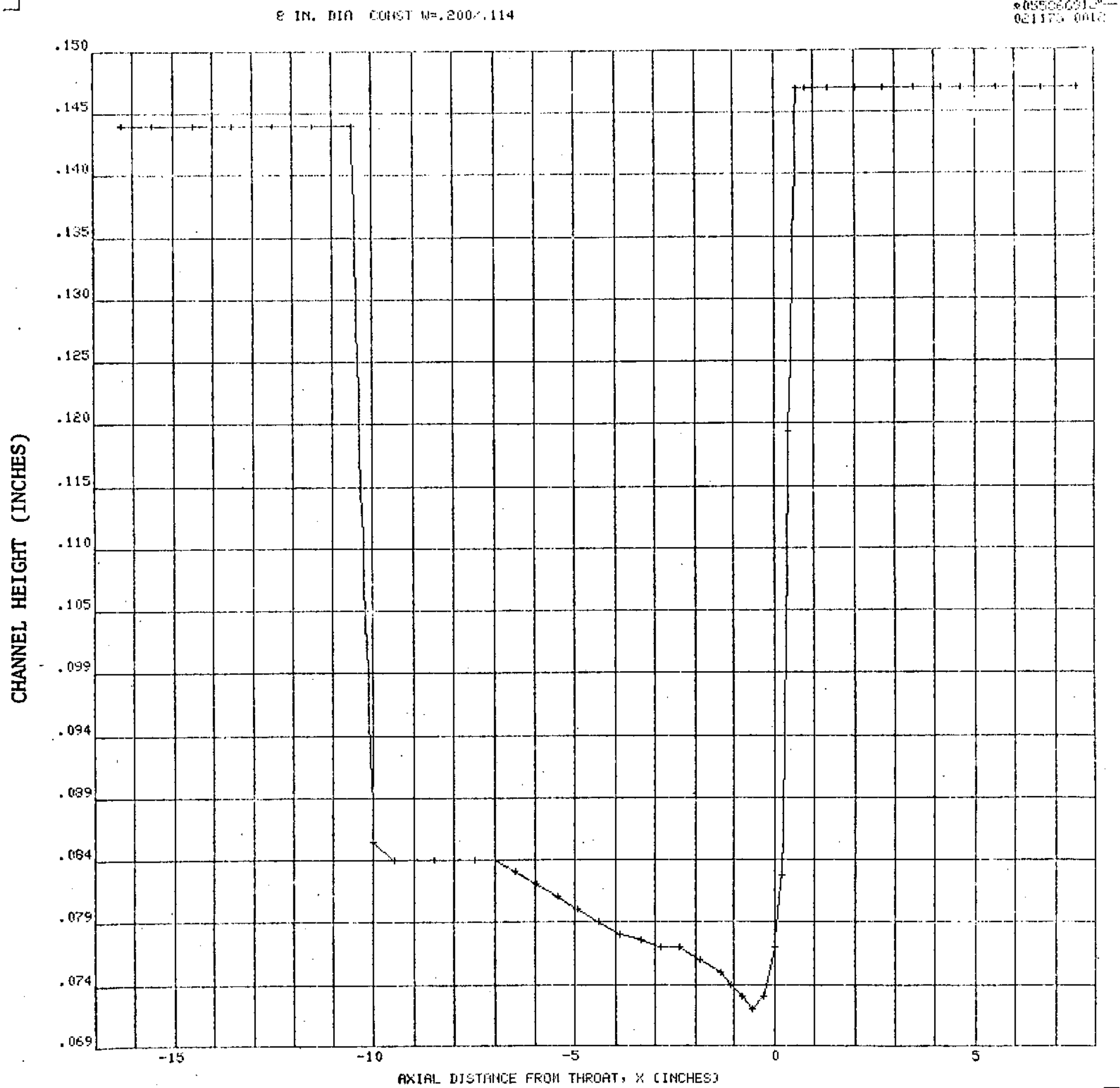


Figure 7. Channel Height Profile For 8-Inch Diameter Chamber - Constant Channel Width Design

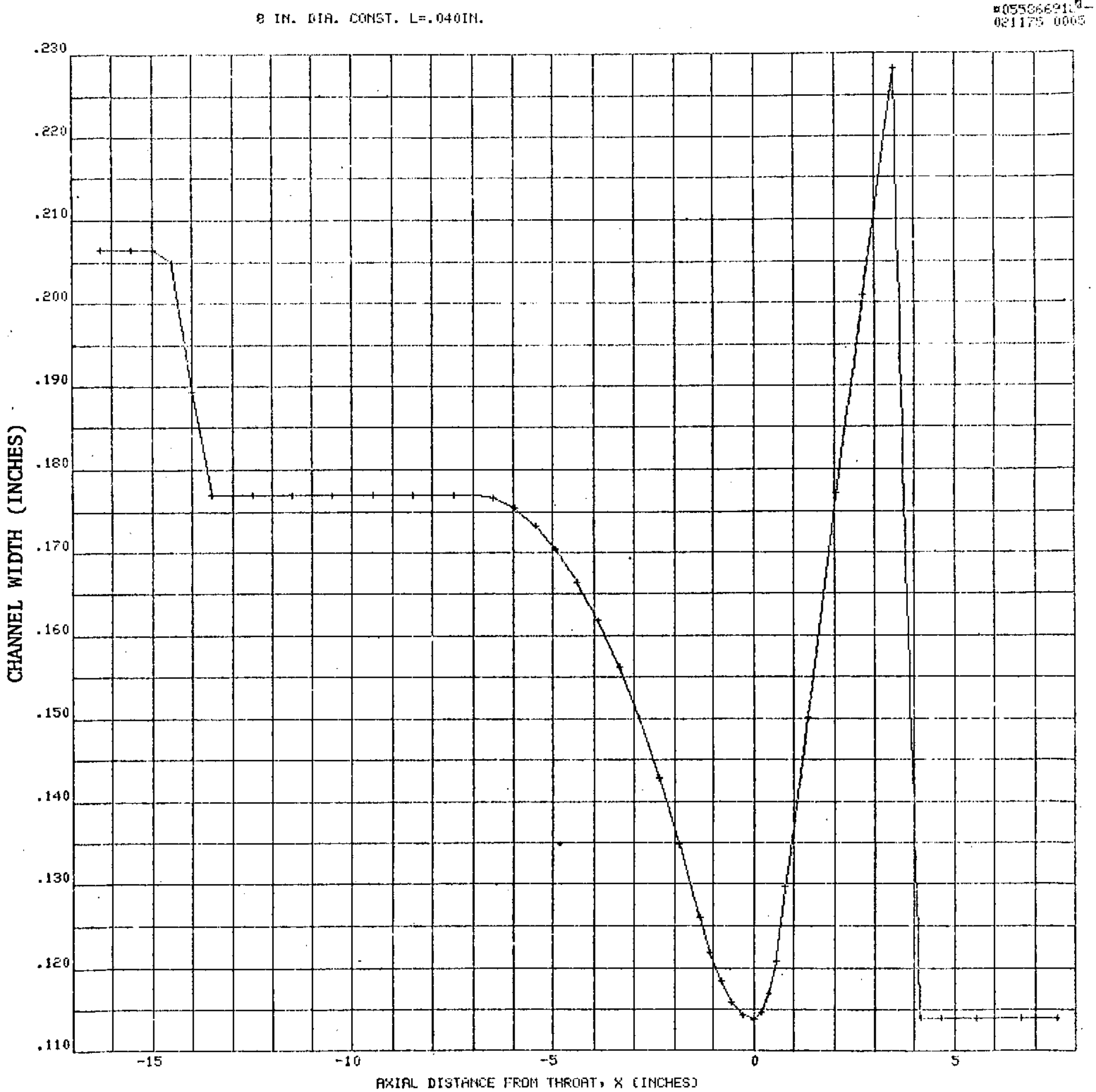


Figure 8. Channel Width Profile For 8-Inch Diameter Chamber - Constant Land Width Design

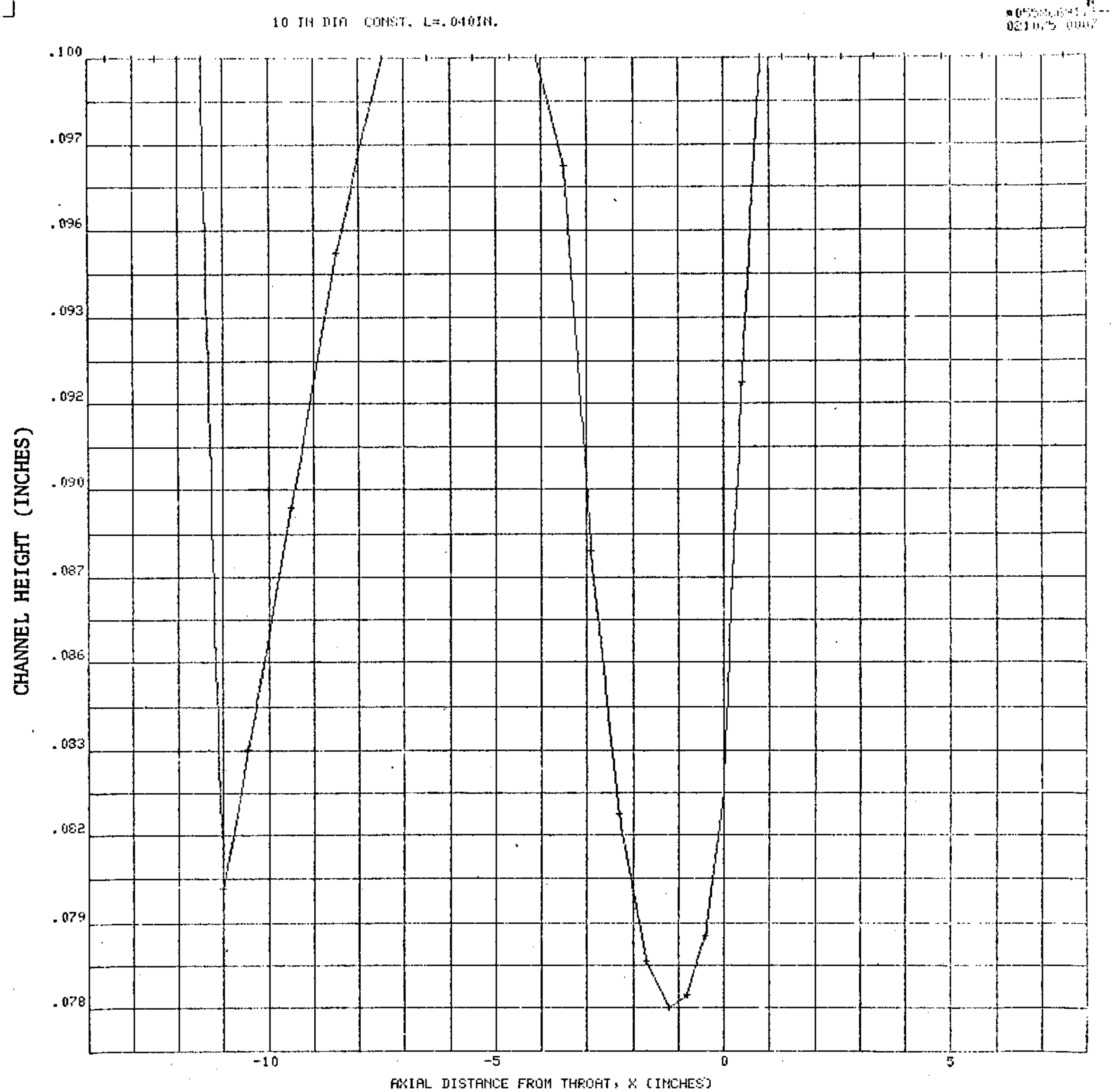


Figure 11. Channel Height Profile For 10-Inch Diameter Chamber Constant Land Width Design



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Figure 9. Channel Height Profile For 8-Inch Diameter Chamber - Constant Land Width Design

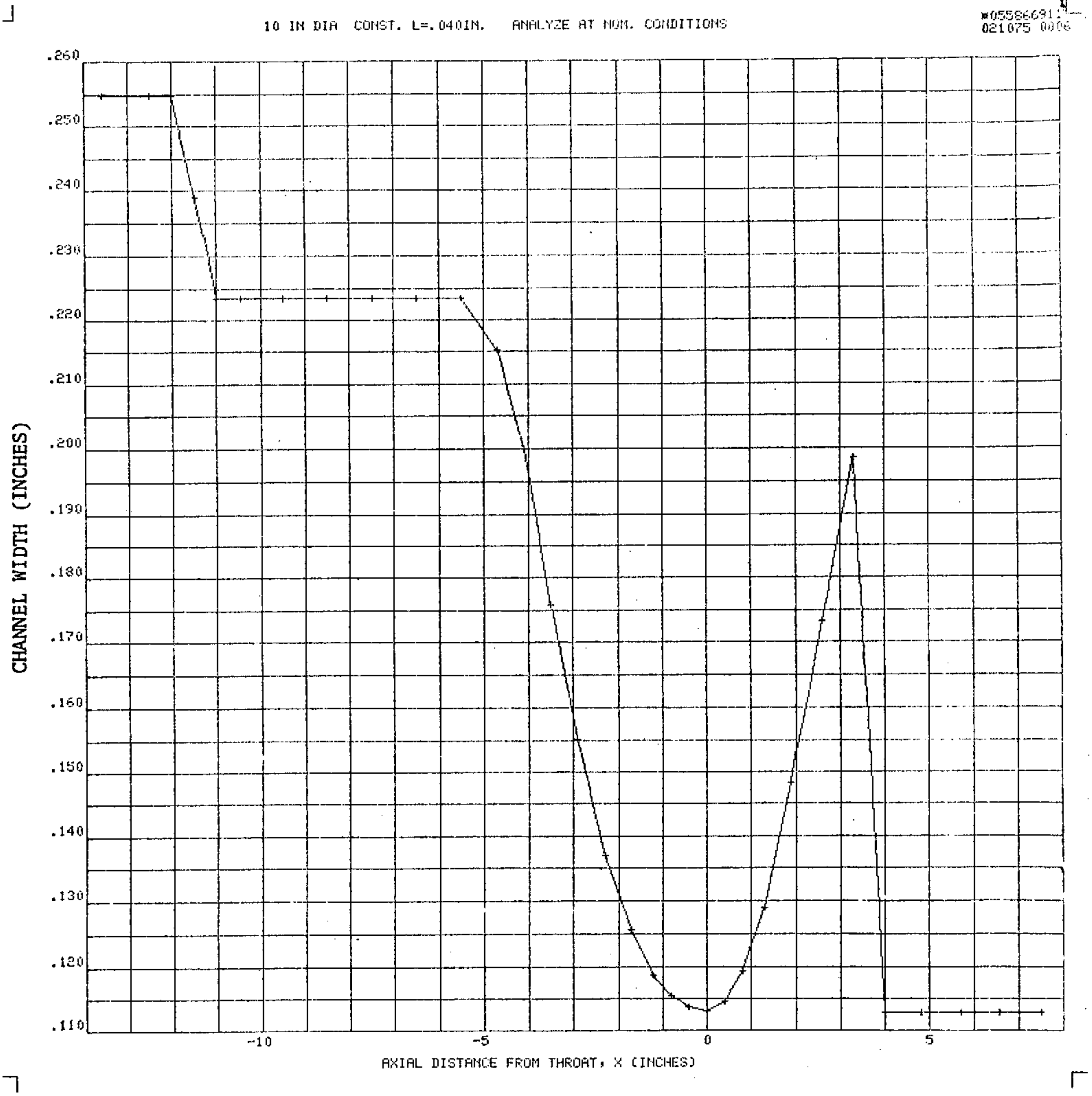


Figure 10. Channel Width Profile For 10-Inch Diameter Chamber - Constant Land Width Design

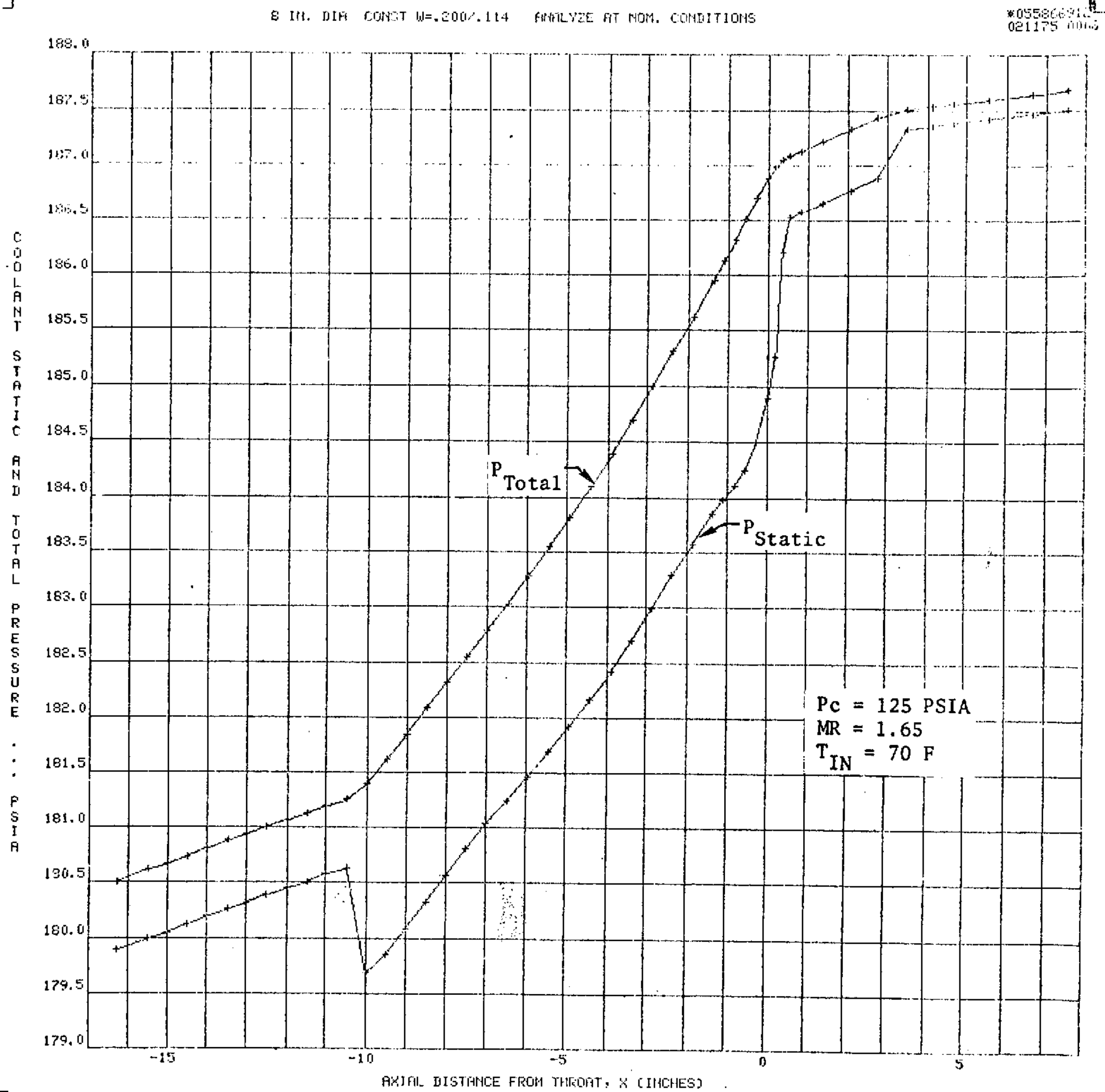


Figure 12. Coolant Pressure Profile For 8-Inch Diameter Chamber - Constant Channel Width Design

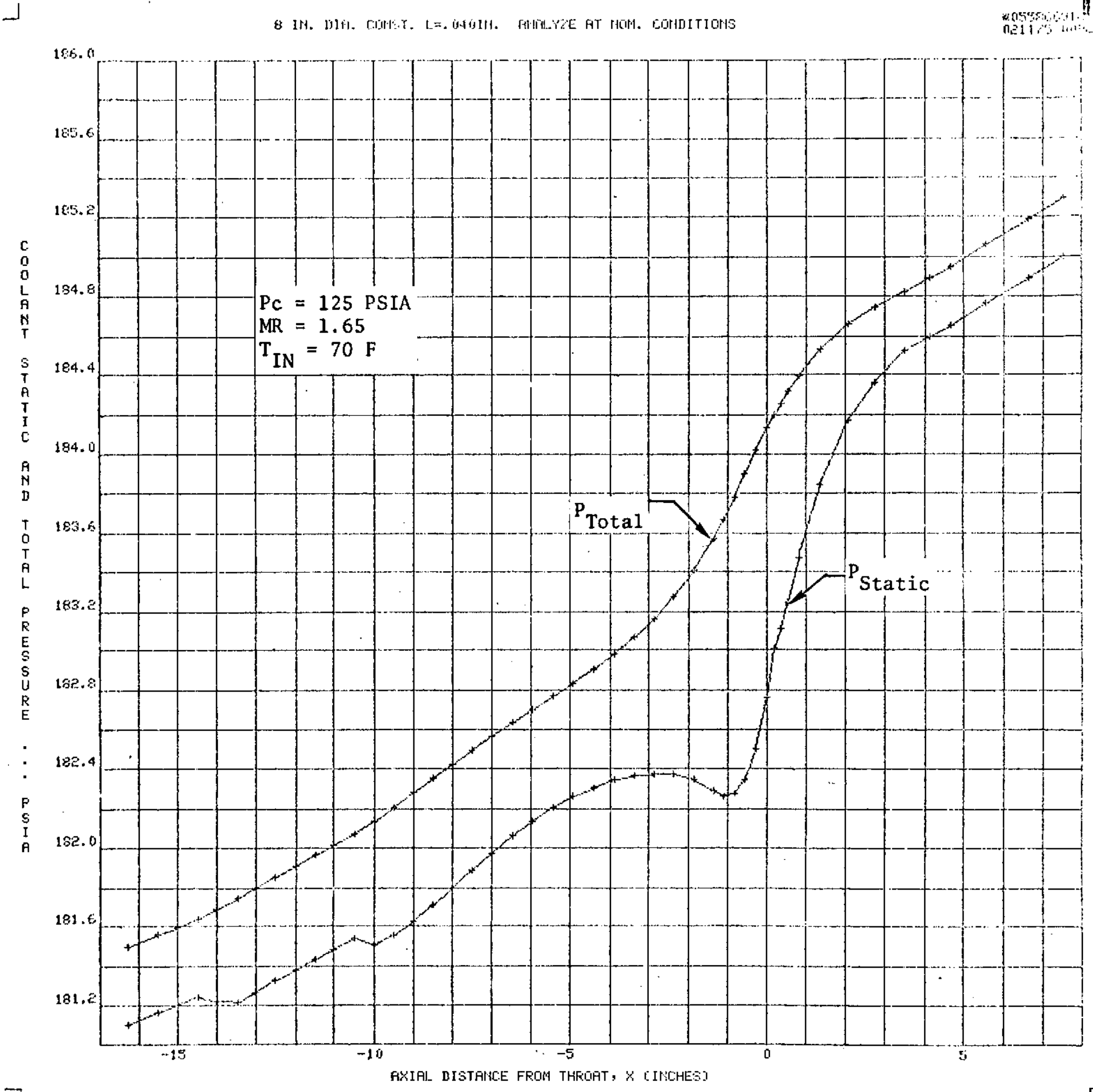


Figure 13. Coolant Pressure Profile For 8-Inch Diameter Chamber - Constant Land Width Design

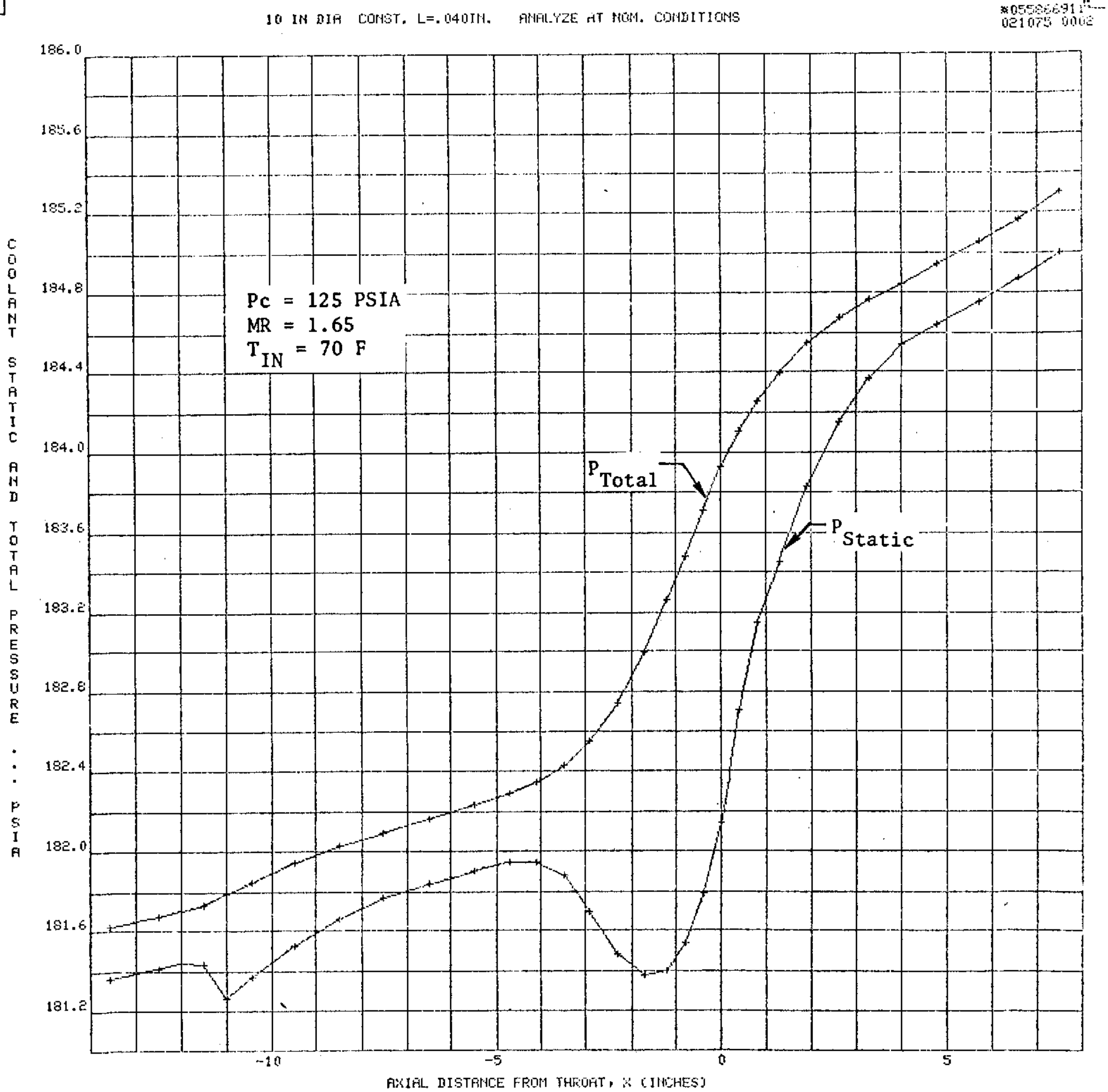


Figure 14. Coolant Pressure Profile For 10-Inch Diameter Chamber - Constant Land Width Design

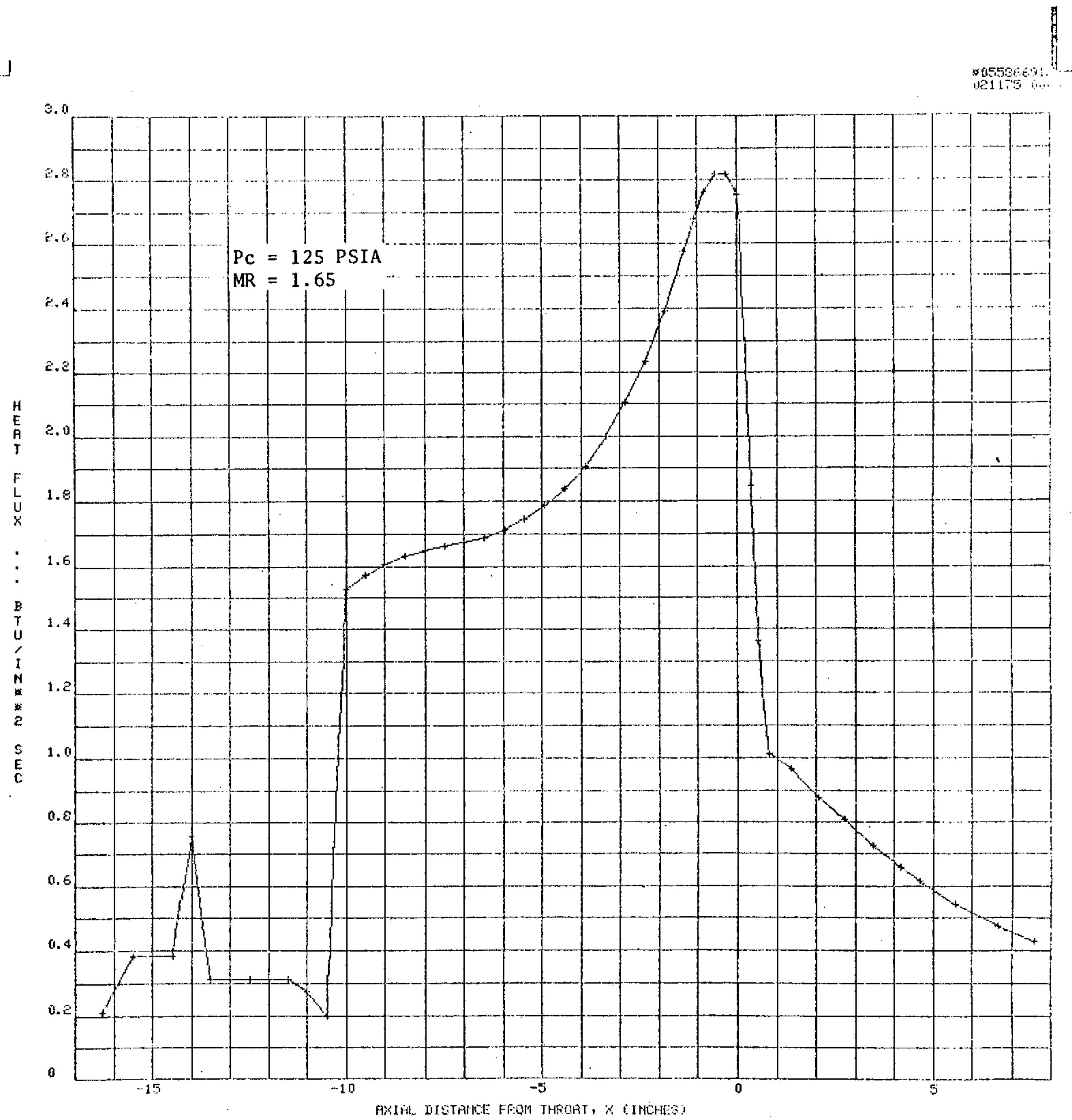


Figure 15. Heat Flux Profile For 8-Inch Diameter Chamber

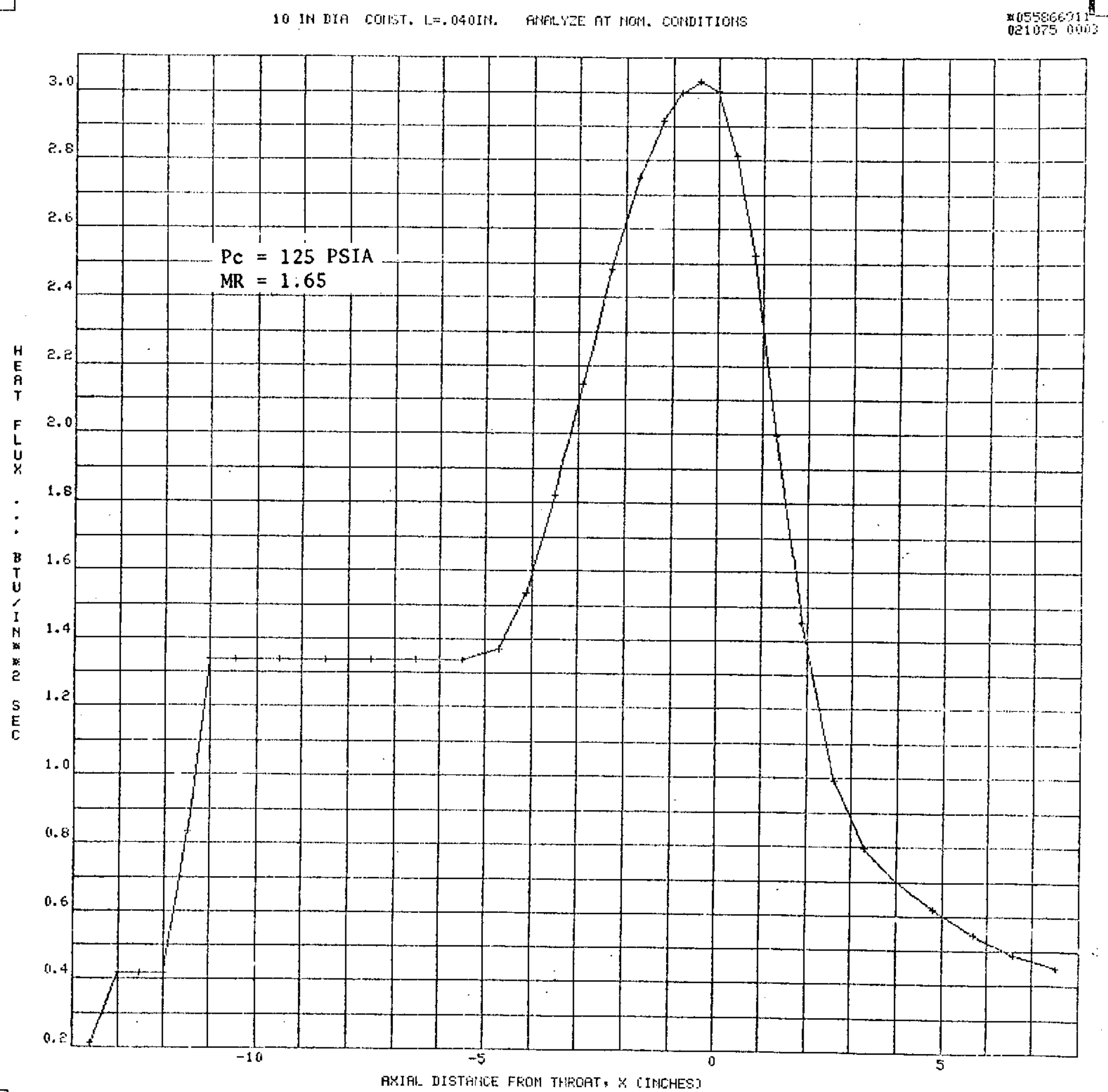


Figure 16. Heat Flux Profile For 10-Inch Diameter Chamber

### Weight and Performance Analyses

Jacket weights were calculated from the channel dimension profiles. Injector, coolant outlet manifold, and radiation nozzle weights for the high contraction chamber were scaled from the low contraction chamber weights. The resulting values (pounds) are tabulated below:

| Construction | $\epsilon_c$ | Jacket | Injector | Manifold | Nozzle | Total |
|---|---|---|---|---|---|---|
| Constant Channel | 2 | 24.0 | 23.6 | 11.4 | 41.2 | 100.2 |
| Constant Land | 2 | 17.5 | 23.6 | 11.4 | 41.2 | 93.7 |
| Constant Land | 3 | 17.0 | 35.4 | 12.1 | 42.5 | 106.8 |

The results presented in NASA Memorandum EP22/M11-74 were used to estimate the performance advantage of the longer nozzle used with the high contraction ratio chamber. The increment was 0.9 seconds specific impulse.

## COMPARISONS AND CONCLUSIONS

Differences in weights and interface pressures were converted to effective specific impulse using the following OMS sensitivity data furnished by the NASA Program Manager

- -4 lb system inert wt/psi interface pressure (oxidizer and fuel)
- 3 lb system inert wt/sec engine specific impulse
- 75 lb system wet wt/sec engine specific impulse

The results are summarized in Table 3 with comparisons made both on the basis of OMS wet weight and OMS inert weight. The chambers having constant width lands are superior to the chamber having constant width channels on either basis. The low contraction ratio chamber is significantly superior (3.2 sec) on the basis of inert weight. Comparison based on OMS wet weight put more emphasis on performance so the longer nozzle of the high contraction chamber gives it a slight advantage (0.7 sec).

TABLE 3

SUMMARY OF THRUST CHAMBER ASSEMBLY CHARACTERISTICS

| Configuration | $\epsilon_c$ | Wt. Difference Lb | Equivalent $I_s$, Sec | | Inlet Press., PSI | Equivalent $I_s$, Sec | | Nozzle $I_s$ Sec | Net Equiv. $I_s$, Sec | | Allowable Loss In $\eta_{c^*}$,% | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Constant Channel Width | 2 | Nominal | Nominal | | Nominal | Nominal | | Nominal | Nominal | | Nominal | |
| | | | Inert | Wet | | Inert | Wet | | Inert | Wet | Inert | Wet |
| Constant Land Width | 2 | -6.5 | 2.2 | 0.1 | -3.6 | 4.8 | 0.2 | 0 | 7.0 | 0.3 | 2.2 | 0.1 |
| Constant Land Width | 3 | 6.6 | -2.2 | -0.1 | -3.8 | 5.1 | 0.2 | 0.9 | 3.8 | 1.0 | 1.2 | 0.3 |